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Policy Informing Brief

The opportunities and challenges of marine carbon accounting - a case study for the North Sea shelf ecosystem and the potential value of the ICOS Oceans Network

Flanders Marine Institute

Policy informing brief

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Details

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Content

Setting the scene

This policy informing brief provides a scientific review of the topic of marine carbon accounting. It discusses the current approach of the relevant environmental-economic accounting frameworks and touches upon the associated challenges and opportunities linked to marine carbon accounting. It also elaborates on the role that the ICOS Oceans Network can play in this emerging and rapidly developing field and seeks to demonstrate how the VLIZ-ICOS Oceans partnership can be at the core of an effective European marine climate strategy and sustainable regional development. Because of its potentially significant climatological relevance, accounting for the underexposed organic carbon of shelf sediments, this ecosystem receives special attention in this brief.

1. Introduction

1.1 Marine carbon sinks

Marine ecosystems play a crucial part in regulating the Earth's climate. The ocean has a natural capacity to absorb about 25% of the annual anthropogenic CO_2-emissions (IPCC 2019, Friedlingstein et al. 2022) and constitutes the largest carbon sink[1] in the biosphere, storing approximately 93% (±40.10^{12} tonnes) of the Earth's dynamic CO_2. Seafloor sediments have the capacity to sequest carbon for hundreds and even millions of years (Burdige 2007, Nelleman et al. 2009, Trumper et al. 2009, Lee et al. 2019, Atwood et al. 2020, Hendriks et al. 2022). Marine ecosystems which capture and sequester carbon are **a key part of the oceanic carbon cycle**, but have remained largely overlooked in relation to their climate regulating potential, despite capturing over half (55%) of all biological carbon (CO_2 for photosynthetic activity) and cycling circa the same quantity of carbon annually (±90 Gigatonnes) as terrestrial ecosystems, while harboring 99.5% less plant biomass (Bouillon et al. 2008, Nelleman et al. 2009, Simon et al. 2009). In addition, the potential climate impact of a threatened and weakened marine carbon sequestration process, resulting in an exacerbation of climate change is becoming a major concern (Luisetti et al. 2019, 2020; Atwood et al. 2020, Sala et al. 2021).

In the marine realm, blue carbon ecosystems (coastal ecosystems consisting of saltmarshes, seagrasses or mangroves) are real carbon sink powerhouses. These ecosystems are in fact the Earth's most effective carbon sinks per unit area, potentially removing up to 17 tonnes/ha of carbon annually (Nelleman et al. 2009, Laffoley & Grimsditch 2009, Mcleod et al. 2011, Macreadie et al. 2019, Dauwe et al. 2021). A feat which has led to an exponential growth of the blue carbon trade market as blue carbon restoration projects provide companies willing to reduce their GHG-impact a powerful offset pathway (see **2.1 Blue carbon and the carbon market**). Further away from the coastline, shelf ecosystems (<200 m in depth, covering around 8% of the global marine area), also exhibit large burial rates and stocks of organic carbon. Because most of the shelf carbon is stored within the sediment, **shelf sediments constitute an important, stable (if undisturbed) and manageable carbon stock**. The size of the latter roughly corresponds to the carbon stock of the Earth's tropical forest (Bauer et al. 2013, Avelar et al. 2017, Bianchi et al. 2018, Diesing et al. 2017, 2021, Lee et al. 2019, Luisetti et al. 2019, Atwood et al. 2020[2], Legge et al. 2020, EEA). Since climate mitigation relies on long-term carbon sequestration, shelf environments (incl. prevailing ecosystems) hence have a very valuable role to play in terms of climate regulation (Smith et al. 2015, Avelar et al. 2017, Luisetti et al. 2019, 2020; Atwood et al. 2020, La Rowe et al. 2020, Sala et al. 2021, EEA). Shelf ecosystems are understudied in terms of carbon storage processes however, with particularly sparse data on local carbon stability and accumulation rates, leaving scientists and decision-makers with a fragmented picture on their climate regulating potential (La Rowe et al. 2020, Legge et al. 2020, Diesing et al. 2021).

1.2 Accounting for marine climate mitigating ecosystem services

It is only fairly recently that debates are being held within administrative circles on whether and how the aforementioned marine carbon sinks need to be considered within national greenhouse gas emissions inventories and potential greenhouse gas mitigation strategies and whether marine carbon stocks should be protected from human-disturbances for climatological reasons (Avelar et al. 2017).

[1] Most of the oceanic carbon is inorganic carbon (bicarbonate, carbonate, dissolved inorganic carbon) with the majority remaining in suspension, although a small portion of inorganic carbon gets buried on the seafloor (Hendriks et al. 2022). Concerning organic carbon, only <1% of the total organic carbon (particulate organic matter (POM) or dissolved organic matter (DOM)) at the sea surface gets buried and stored permanently on the seafloor (Burdige 2007, Atwood et al. 2020, Hendriks et al. 2022).

[2] It is estimated that globally, 3,117,000 Mton (megatonnes, 1 megaton = 1.10^6 tonnes) of organic carbon is stored within the top 1 m ocean floor (Atwood et al. 2020).

To be able to make underpinned choices in this debate, a scientifically based, **transparent marine carbon accounting system** is indispensable (see **3.2 Marine carbon accounting**). Valuing stocks and flows of carbon, is a growing approach for inventorying greenhouse gasses and embedding that information into decision-making and reporting among governments, companies, and stakeholders. With the increasing urgency of carbon dioxide removal techniques and net-zero emission pathways, standardized, transparent and practical carbon accounting guidelines and government frameworks too are **increasingly desired** (Cavalletti et al. 2020, COM (2021) 800, Dasgupta 2021, Alarcon Blazquez & van der Veeren 2021, UN 2021, ICAP 2022, Marlowe & Clarke 2022, EC Climate Action, EC public consultation on the certification of carbon removals). Because of its major societal relevance, the field of carbon accounting is evolving at a rapid speed, but issues on clarity, methodology, etc. highlight the need for an increased attention in this dynamic research-policy area (see **3. Environmental-economic accounting**).

Notably in the field of marine carbon accounting, a lot of **knowledge gaps** and **many barriers persist** to evaluate if and how the ecosystem service of marine carbon sequestration needs to be taken into account in environmental-economic accounting schemes. A key issue in the context of climate mitigation is the **lack of spatial data on the magnitude of carbon stocks and fluxes** and insight on how the carbon passes through the system, the so called '**fate of the carbon**' (Atwood et al. 2020, La Rowe et al. 2020, Legge et al. 2020, Luisetti et al. 2020, Diesing et al. 2021). The transboundary nature of carbon flows in the marine environment also poses a significant challenge for carbon accounting, requiring new international guidance and governance frameworks for its management (Luisetti et al. 2020). Also, CO_2 emitters and beneficiaries of marine carbon sequestration aren't necessarily the same entities. In addition to carbon sequestration, marine ecosystems also provide a whole range of **ecosystem services**[3] that are valuable in sustaining the Blue Economy, our own wellbeing, or are of great natural value (UN SDG14, Hoegh-Guldberg et al. 2015, Hooyberg et al. 2021, Joliffe et al. 2021, SOPHIE-project), hence trade-offs with other social welfare benefits, like for instance food provision, need to be taken into account when accounting for marine carbon sequestration and drafting climate policies (Luisetti et al. 2019). The relationship between these elements has led to marine ecosystems **not yet receiving the same attention** as land-based ecosystems when it comes to developing integrated, practical and internationally accepted carbon accounting and legislative frameworks (Luisetti et al. 2020).

1.3 The advantages of the North Sea area

The North Sea area is one of, if not, the best studied shelf sea in the world (Legge et al. 2020). Hence, it can serve as **an ideal pilot** for European policymakers and stakeholders to push for the development of a fit for purpose marine carbon accounting system and marine carbon dioxide removal incentivizing policy frameworks (Avelar et al. 2017, Fuso et al. 2019, Dvarskas 2019, Luisetti 2019, 2020, Thornton et al. 2019, Alarcon Blazquez & van der Veeren 2021, Grilli et al. 2022, EC public consultation on the certification of carbon removals). The area would benefit a great deal from a strong, science-based marine carbon accounting framework since it needs to accommodate a large and growing **Blue Economy**, while also housing various precious habitats. Equally important, the North Sea area offers significant **climate mitigating opportunities**[4] for some of Europe's largest GHG emitters (Dauwe et al. 2021). A major point of concern, however, is the sustainability of its carbon balance, since seafloor-disrupting activities (bottom trawling[5], dredging, etc.) frequently occur in the region which may cause significant damage to bottom life, a depletion of the carbon stocks and a rerelease of CO_2 to the atmosphere (Halpern et al. 2008, Pusceddu et al. 2014, Hiddink et al. 2017, Atwood et al. 2020, Legge et al. 2020, Luisetti et al. 2019, 2020, Roobaert et al. 2019, De Borger et al. 2021, Black et al. 2022, Epstein et al. 2022). Because of the challenging hydrodynamic conditions, there is a real concern these activities might result in short-term harmful (year or less) **climate and societal consequences**, entailing great economic costs (Luisetti et al. 2019). Since the North Sea is surrounded by several, densely populated countries, having a clear picture of its **carbon balance** and having this translated into environmental (carbon) accounting schemes, is thus very informative in the light of national GHG-balance inventories, climate strategies and marine spatial planning.

[3] Ecosystem Services (ES) are generally defined as the benefits society receives from nature. However, the way ES within various practical applications and frameworks are applied, defined, quantified, modelled, valued and communicated ranges widely, potentially hindering their roles as cross-sectoral tools (Boyd & Banzhaf 2006, Apitz 2013). Nevertheless, the concept provides a useful organizing framework when linking environmental assets to the economy (Dunford et al. 2018).

[4] When looking solely at Carbon Capture and Storage (CCS), the carbon storage potential of the North Sea is estimated to be between 134-200 Gton CO_2 (GCCSI 2019, Terlouw et al. 2019, North Sea Energy 2020, Baines & Lashko 2020, CO_2 Storage Resource Catalogue). This capacity corresponds to about 1,500 times Belgium's annual CO_2 emissions and is theoretically sufficient to store 300 Mtonnes of CO_2 annually for more than 400 years (the target if we want to limit global warming to1.5°C according to the 1,5TECH scenario – COM (2018) 773 – A clean planet for all). The potential contribution of other climate mitigating measures (e.g. offshore renewable energy, ecosystem restoration, etc.) on policy choices and answering obstacles, but the potential is again in the order of millions of tonnes of CO_2 emissions saved (Dauwe et al. 2021).

[5] On a global scale, Sala et al. 2021 estimated that fishing trawlers mobilize about 1.47 billion tonnes of CO_2 each year – roughly the same size of the entire aviation industry and exceeding the mitigation potential of blue carbon ecosystems, including seaweed. Where all this carbon eventually ends up and how sizeable the proportion that reaches the ocean surface is, is unknown.

A major opportunity is the fact that carbon fluxes in the North Sea area are being monitored by the marine component of the Integrated Carbon Observation System (ICOS Oceans Network). The ICOS Oceans Network (see **6. The potential of ICOS Oceans Network**) is an international collaboration of 23 marine stations spread over eight different countries providing **qualitative and accurate measurements of carbon concentrations** in surface seawater in the North Atlantic, Nordic Seas, Baltic, and the Mediterranean Sea. This pan-European research infrastructure can thus play an important role in the scientific underpinning of government measures on climate change or regional development, next to making an important contribution to the development of sound **marine carbon accounting practices**.

2. Pricing CO_2 emissions

In the fight against climate change, several countries around the globe have implemented or plan to introduce carbon emission pricing measures, differing in scope, coverage (sector exclusions) and boundaries (regional-national scale). Since the late 1990s, no less than 64 different carbon pricing instruments were established worldwide[6], covering 21.5% of all global emissions by a carbon credit mechanism (Joliffe et al. 2021, World Bank 2021).

Since crediting for carbon gives it **added value**, the principle of buying carbon credits (one credit equals one ton of CO_2 to be emitted, or the mass equivalent to CO_2 for other greenhouse gasses (GHG)) to offset emissions, **can be an effective mechanism in curbing GHG emissions**, however the level of emissions covered remain limited (**figure 1**) and there is the risk of "carbon leakage" (companies moving their operations to zones without emissions credits) (Remeur 2020, Joliffe et al. 2021, World Bank 2021, ICAP 2022[7]). Emissions trading is already regarded as an **indispensable policy tool to decarbonise the global economy** and its importance is only expected to increase in the future. From this perspective, a widely and **correctly applied carbon accounting system is an absolute prerequisite** (ICAP 2022).

The theory behind putting a monetary value on GHG emissions (expressed as a monetary unit/ton produced carbon dioxide equivalent (CO_{2e})) is to trigger the polluter into making its enterprise more environmentally friendly. The CO_2-fee to be paid is thought to represent the estimated 'social costs' or negative externalities, in accordance with the 'polluter pays' principle (see **Appendix 9.1 The social cost of carbon (SCC)**). In essence, the goal is to make **the financial impact of not reducing GHG-emissions higher than the cost of implementing GHG-mitigating measures**. Credits decay over time, meaning companies continuously need to come up with new ways to reduce their emissions. Since the principle isn't limited to the energy sector, or industry in general, but also applies to transport, land-use, consumer behavior, etc., the **CO_2 price isn't universal** (ICAP 2022). A whole range of challenges and questions arise when trying to standardise its accounting principles and making sure carbon pricing mechanisms serve their purpose **without putting a brake on national and global economic developments** (Remeur 2020, ICAP 2022). The carbon market also suffers from a troubled history as dubious practices like double counting of CO_2-reductions, the failure to transfer money to local communities, the plantation of monoculture forests, or the creation of collateral environmental and societal damage along the way has dented its good intentions (Nesshöver et al. 2017, Seddon et al. 2020). There is also a need to ensure that companies reduce their emissions before resorting to buying carbon credits to offset the remaining emissions.

Carbon markets exist both under compliance (carbon credit) schemes and as voluntary (carbon offset) programs. **Compliance markets** are created and regulated by mandatory regional, national and international carbon reduction regimes, such as the Kyoto Protocol (1997) and the European Union's Emissions Trading Scheme. **Voluntary offset[8] markets** function outside of compliance markets and enable companies and individuals to purchase carbon offsets on a voluntary basis. Carbon offset projects can be divided into two categories: 1. Avoidance or reduction projects (e.g. wind and solar energy); 2. Removal or sequestration projects (e.g. afforestation, restoration of blue carbon ecosystems, direct air capture (DAC)). Presently, the carbon trading on the voluntary carbon market has to be viewed as **a natural market response** to an emerging demand without clear established criteria on eligible carbon offset projects. Currently, work is undertaken by members of the UN Framework Convention of Climate

[6]Not only do carbon credit mechanism exist, but also biodiversity credits, plastic credits, etc. all sharing the same principle and goal (South Pole).
[7]According to data from the International Carbon Action Partnership, by the end of 2021 ETSs covered 37 % of emissions in jurisdictions that have enshrined their net-zero targets in law and 17 % of emissions in jurisdictions where net-zero targets are under development or discussion
[8]The (voluntary) carbon market (VCM) sells carbon offsets, which are measurable, quantifiable, and trackable units of GHG emission reductions. Confusing guidelines ultimately limit the effectiveness of both the VCM and government policy, leading to the fact that the current systems may work against each other rather than reinforcing each other (Climate Focus).

Change (UNFCCC) to modify Article 6 (notably 6.4 'Sustainable Development Mechanism (SDM)), which governs how countries can use carbon markets to reach their government-imposed targets, to help guide and stimulate the voluntary carbon credit market (UNFCCC news).

In the EU, Member States (MS) have to offset all deforestation either by equivalent afforestation or by improving sustainable management of existing forests (Land use and forestry Regulation for 2021-2030, LULUCF Regulation (Regulation (EU) 2018/841)). This is known as the "no debit" rule. MS already partly undertook this commitment individually under the Kyoto Protocol up to 2020, whereas the LULUCF Regulation encompasses the commitment for the first time in EU law for the period 2021-2030 (EC Climate Action). In this respect, the Regulation simplified and revised EU's carbon accounting methodology, while also broadening the scope to encompass all managed land uses (including wetlands by 2026). However the Regulation doesn't tailor to the marine/maritime context, possibly because land-based efforts are easier to plan and scale up and are generally cheaper.

The carbon pricing landscape can generally by subdivided into two mechanisms: explicit carbon pricing and implicit carbon pricing (oversimplification) (World Bank 2021). In the following, these two mechanisms are further elaborated.

2.1 Explicit carbon pricing

Explicit carbon instruments are **enacted by a government** mandate and impose a price based on carbon content. In practice, it either concerns imposing **a carbon tax or an Emission Trading System (ETS)**. Often, cap and trade systems and carbon taxes generate a certain revenue for governments, which can subsequently be used to work on other development goals (World Bank 2021).

2.1.1 Carbon tax

When opting for a carbon tax, the government determines the price and lets market evolutions determine the realized emission reductions. The tax puts an explicit price on GHG-emissions or uses a metric that is directly linked to the GHG-emissions. A tax is applied on the notion that greenhouse gasses bring forth a set of negative externalities to society, which come at a certain cost (see **Appendix 9.1 The social cost of carbon (SCC)**). The key difference between the ETS-principle (see below) is that a tax **provides price certainty** (Remeur 2020, World Bank 2021). A carbon tax guide for policymakers is provided by the World Bank (PMR 2017).

2.1.2 Emission Trading System (ETS)

Presently, several national and international regulated and voluntary markets for trading carbon emission credits are in place. In general, two approaches are followed: cap-and-trade and baseline-and-credit. In a cap-and-trade systems, the government sets a "cap" on the amount of emissions in a particular period (year) and allowances or permits that make up the cap are either auctioned or allocated (trade), or a combination of both (Remeur 2020, World Bank 2021, Marcu et al. 2022). The carbon **price is determined by the carbon market**. The system has predominantly been used in the energy and heavy industry sector.

Under a baseline-and-credit system, baselines are set for regulated emitters. Emitters with emissions above their designated baseline need to hand in credits to make up for the extra emissions. Conversely, emitters that have reduced their emissions below their baseline receive credits that they are allowed to sell to other emitters.

2.2 Implicit carbon pricing

Implicit carbon pricing is used in a whole range of ways, but it comes down to governing bodies imposing a compliance cost (an implicit price) on activities that emit GHGs. Estimating implicit carbon prices requires a certain quantification approach, which often proves complex. Implicit carbon pricing policies and the methodologies used to calculate these prices are often debated (World Bank 2021). It is however, c**onsidered to be a very effective decarbonization policy** by rendering low- and zero carbon energy activities more competitive compared to CO_2-intensive alternatives (Joliffe et al. 2021). The best-known example is the **effective carbon rate** (EUR/tCO_2) which is composed out of the sum of the tradeable emission permit prices, carbon taxes and fuel excise taxes.

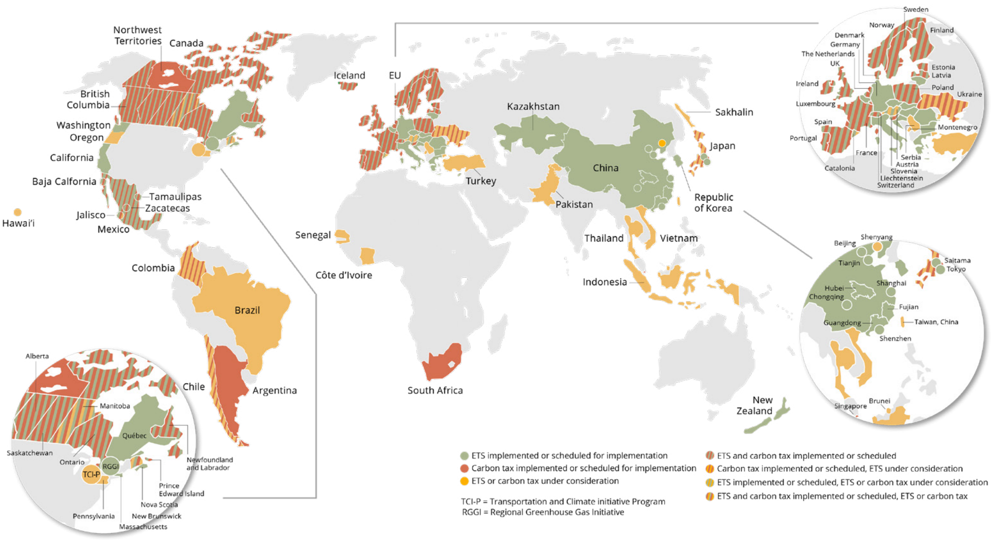

Figure 1. Geographic visualisation of the different carbon pricing mechanisms in place globally (2021) (World Bank 2021).

An overview of the current situation in the global carbon pricing landscape and emission trading can be consulted in World Bank (2021) and ICAP (2022). A summary on Europe's carbon pricing mechanisms can be consulted in Remeur (2020) and EC Climate Action.

2.3 Blue carbon and the carbon market

In parallel with the growing recognition that marine ecosystems can act as powerful carbon sinks, there is also **growing interest in trading marine carbon (storage) in the international carbon market** (Carbon Credits, Yale Environment360). To date, the marine carbon offset trading market basically entirely revolves around blue carbon (BC) ecosystems (salt marshes, mangroves, seagrasses, see **1.1 Marine carbon sinks**). With blue carbon markets, projects that protect or restore these ecosystems (a popular nature-based solution (EC Environment)) can **generate offsets** based on the amount (tonnes) of carbon that is projected to be captured and stored. These offsets are sold to companies that want to compensate for their carbon emissions. Especially **sectors from the Blue Economy** (shipping industry, tourism) are keen to invest in the natural capital they're impacting (Yale Environment360). According to Hoegh-Guldbergh et al. (2019), protecting and restoring these ecosystems could reduce CO_2-emissions by up to 1.4 billion tonnes annually by 2050. Next to great carbon removal prospects, blue carbon ecosystems provide a **range of benefits for society** and the environment like coastal protection or improved biodiversity, hence making blue carbon offsets a desired, qualitative but priced prospect for investors and traders (prices generally range between 2-20 $/tonnes (Ocean Economist)) (Carbon Credits, Yale Environment360). However, restoration projects are generally expensive and **questions on the stability of carbon stocks** when threatened by climate change, severe storms or other impacts are valid points of concern for offset buyers. To ensure that investors receive as qualitative and reliable carbon offsets as possible (buyers demand guarantees that purchased GHG-reductions are clearly achieved), offset **verification-certification** services like those provided by Verra (Verified Carbon Standard (VCS) programme) or Plan Vivo (Plan Vivo carbon offset guide) are very important to safeguard the credibility of the market.

The blue carbon market does not (yet) fall under existing government regulation, but offsets are bought and sold on the **voluntary carbon market**[9] (see **2. Pricing CO_2 emissions**). Blue carbon markets are also relatively new compared to their terrestrial counterparts (e.g. reforestation projects in the Amazon) but revenues are projected to grow exponentially in the coming years (some estimate its total projected value to be worth over 50 billion USD by 2030 (Task Force on the Voluntary Carbon Market 2021).

It has been demonstrated that, when managed well, blue carbon restoration projects **can support the most vulnerable communities affected by climate change** (Hoegh-Guldberg et al. 2015, Vanga Blue Forest project, Vida

[9] Nori, Gold Standard and Carbonplace are examples of major marine (blue) carbon offset traders.

Manlar project, Mikoko Pamoja project). However, it is imperative for its success to educate and gain the trust of the local communities and making sure they reap the rewards of the restored ecosystem. The best studied and most advanced blue carbon credit projects are those associated with the restoration of mangroves (Murdiyarso et al. 2015, Zeng et al. 2021, Ocean Economist). **Mangrove ecosystems are currently the best understood BC ecosystems** in terms of carbon flow and how to organize successful restoration projects. Nevertheless, scientists are putting a lot of effort into correctly accounting for marine carbon sequestration in other ecosystems than blue carbon ecosystems, like **seaweed and seafloor sediments**, so that they too can be traded with the necessary reliability as carbon offsets on the international carbon market (Sala et al. 2021) (see further **3.2.1 Accounting for marine shelf carbon**). However, to proceed, major questions on the fate of the carbon and stability of these potentially huge carbon sinks need to be answered in addition to clarify a whole range of methodological issues surrounding the correct application of environmental-economic accounting principles (see **3. Environmental-economic accounting**).

3. Environmental-economic accounting

Today, national economies are compared by an internationally recognized and standardized system, the 'System of National Accounts' (SNA). The SNA is organized around **a set of tables using exchange market values** as its measuring unit. The best-known metric is the Gross Domestic Product (GDP). However, the limitations of the GDP in providing a holistic and accurate assessment of the wellbeing of a country has long been criticized (EEA 2019, Fenichel et al. 2020, Dasgupta 2021). Particularly its economic-centered focus, omitting social, environmental and sustainability considerations raise concern. To overcome this, international efforts are ongoing on the development of metrics that can either **supplement or adjust metrics such as GDP** to better account for the overall wellbeing of society and the state of the environment. These efforts have for instance resulted in '**Green Performance Indices**' like the Genuine Progress Indicator (GPI), the Inclusive Wealth Index (IWI), the Human Development Index (HDI), the Gross Ecosystem Product (GEP) (Ouyang et al. 2019), etc. (Cavalletti et al. 2020, UNEP).

Under the premise that the environment is important to society and the economy, and that it should be maintained and managed, the concept of **natural capital accounting (NCA)** came about. The overarching aim of NCA[10], which is considered the umbrella term for the principle of environmental-economic accounting, is to develop and apply accounting schemes that allow for a better **integration of natural resources into commonly used (economic) frameworks** like the SNA (Natural Capital Protocol[11] 2016, EEA 2019, Turner et al. 2019, Bateman & Mace 2020, Alarcon Blazquez & van der Veeren 2021).

An important driver behind the integration of natural capital into environmental-economic accounting is to **support policy makers** in the implementation of multilateral environmental or societal agreements like the UN Framework Convention on Climate Change (UNFCCC) or the UN Sustainable Development Goals (SDGs) (Bateman & Mace 2020, Cavalletti et al. 2020). At the international level, the Agenda 21 action plan was the first to call for the integration of natural and economic accounting fields in order to be able to **monitor the transition towards an environmentally, socially and economically sustainable future** (UN Conference on Environment and Development 1992). One of the earliest European attempts were initiated by the EU COM (94) 670 – *on Directions for the EU Environmental Indicators and Green National Accounting* (1994). Today, the best-known global example is likely the Sustainable Development Goals (SDGs) of the United Nations. These goals represent an international approach to tracking thematic indicators of wellbeing going beyond the GDP, as many of its themes and goals ty up social, environmental and economic measures.

Developing a robust environmental accounting system involves setting-up a **standardised framework** to systematically (and realistically) describe and link the often complex connections among the stocks and flows of natural resources with the socio-economic system and make a translation to the corresponding **flow of monetary**

[10] Belgium applies the NCA-approach to account for the supply and use of ecosystem services (e.g. wood production, carbon storage in aboveground biomass, health benefits of green and blue spaces). NCA is predominantly used to track the evolution towards the SDGs and in support of Green Economy Indicators. Climate related aspects (climate regulation in urban environments, drought, etc.) are a major political concern. The main knowledge gaps and difficulties are the availability of relevant data, knowledge and skills to build reliable ES-models (which is complicated by Belgium's fragmented political entities) (Alarcon Blazquez & van der Veeren 2021).

[11] The Natural Capital Protocol (NCP) (Natural Capital Coalition 2016) first emerged in the private sector and was initially developed with an orientation towards users at the firm or project level. Its protocol originally consisted out of a series of questions or steps to be integrated into existing business operations. In its basic form it can be best understood as a process for incorporating natural concerns into decision making, rather than as a set of accounting principles. The application of NCA still suffers from a range of conceptual and methodological issues before it can be used in policy or decision-making (Turner et al. 2019).

costs and benefits within a geographic region and time (Bateman et al. 2011, Hein et al. 2015, 2020, Barbier 2019, Bateman & Mace 2020). Workable concepts and clear, **internationally accepted conventions** are a prerequisite for such a challenging exercise to be successful. A major advantage however of environmental-economic accounting (UN-SEEA) is that end-users and policymakers are given a tool to allow a **statistical evaluation** of environmental and economic policy measures (e.g. carbon taxes, payment schemes for ES, subsidies for environmental protection, etc.) (Cavalletti et al. 2020) and provides them the opportunity to quantitatively monitor progress towards supra-national targets like the Climate goals or the UN SDGs. As knowledge and application of EEA grew, so did the recognition that EEA can be a key instrument in combating and evaluating major societal challenges like global warming or sustainable development (Bateman et al. 2011, Costanza et al. 2017, Graveland et al. 2017, Barbier 2019, Diaz et al. 2019, Bateman & Mace 2020, Hein et al. 2020, Dasgupta 2021, Marlowe & Clarke 2022, EC Climate Action).

Since 2012, the 'United Nations System of Environmental-Economic Accounting' (SEEA) provides the internationally accepted standard accounting system for EEA. It is composed out of a Central Framework (CF)[12] (covering assets like fish, water, etc.) (UN 2014) and an ecosystem accounting (EA) component (covering services like climate regulation, recreation, etc.) (UN 2014, UN 2021, UN SEEA-Methodology). SEEA-EA allows for a standardised accounting approach for **a subset of environmental issues** (e.g. natural resource use, extent of emissions, discharges to the environment) and combines and transforms measures of economic activities and environmental information, like the extent and condition of stocks and flows of services and benefits (**figure 2**) (UN 2014, EEA 2019, UN 2021, Gacutan et al. 2022, UN SEEA-Methodology). A major advantage of SEEA-EA[13] comes from the fact that this is an environmental economic accounting approach which observes the environment from an '**ecosystem perspective**' basing itself on the concept of 'ecosystem services'[14,15] (ES) to integrate the stocks and flows (biophysical metrics) they produce to economic activities or disciplines (monetary values).

In essence, ecosystem accounts provide spatially explicit, location-based information including the following information (simplified listing, for a more detailed insight including exameples from the marine context see (Graveland et al. 2017, UN 2019,2021, Grilli et al. 2022 and in part also Dvarskas 2019)):

- Accounts of the ecosystem **extent**;
- Account of the ecosystem **condition** using biophysical indicators (e.g. vertical oxygen profile, nitrate concentration, dissolved organic carbon content, etc.);
- Ecosystem **flow accounts** and their use by society, **quantified in physical and monetary terms**;
- Ecosystem **asset accounts in monetary terms**, giving information on ecosystem stock values (including changes).

By combining this information, the final SEEA-EA tables serve as an instrument to **correlate economic-environmental impacts with policies**. For instance, if ES are measured in a consistent manner over a longer (uninterrupted) period, these tables are able to demonstrate the **state and trends within the ecosystem and should allow for a timely identification of common threats, targeted research, measured decision-making and effective management strategies** (Hein et al. 2015, Barbier et al. 2017, Costanza et al. 2017, Dunford et al. 2018, Vardon et al. 2018, EEA 2019, Dvarskas 2019, Cavalletti et al. 2020).

Since its conception, several attempts have been made to apply ecosystem accounting on a local to continental scale using the UN guidelines. However, these studies identified several issues with the mechanism, arguing that the SEEA-EA guidelines couldn't yet be conceived as a recognized accounting system like NSA/GDP. In response, the UN emphasized **the need to experiment with its implementation** to improve the application of the SEEA-EA tables and integration into policy and decision-making (Experimental Ecosystem Accounting (E(E)A) (Graveland et al. 2017, UN 2019)). In order to stimulate methodological advances, the UN initiated its own revision process guided by a range of targeted international projects (NCAVES, ANCA, WAVES, MAES[16], MAIA).

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[12] The Central Framework establishes an internationally agreed set of standardised concepts, definitions, classifications, accounting rules and tables to produce internationally comparable statistics on how economic activities depend on natural assets or stocks (UN 2014, 2019).

[13] The SEEA-EA system runs on two major components: physical data through spatially explicit ecosystem maps and accounting tables and (ii) economic measures where the physical data are monetised using exchange rates. The system relies on spatial datasets connecting ecosystem service and condition indicators to Land Cover Ecosystem Units (LCEU) and eventually Ecosystem Assessment Units (EEA 2019, Dvarskas 2019). The result is presented in tables with accounting values.

[14] The benefits to society provided by natural ecosystems (Haines-Yong & Potschin 2012). The IUCN Global Ecosystem Typology is used as reference classification.

[15] Boyd & Banzhaf (2006) emphasise the need for standardised environmental accounting units, arguing that the concept or definition of ecosystem services remains too *ad hoc* to be of practical use in welfare accounting and they propose an economic-based definition of 'ecological service units'.

After a global reevaluation, including testing, consultations and revisions with over 100 experts from different countries, sectors and disciplines and an assessment by more than 500 experts, the UN presented a **revised SEEA-EA framework** in March 2021 (UN 2021). According to the UN, this new integrated, comprehensive statistical framework should provide policymakers, the business sector, and other stakeholders with a workable tool to quantify and track changes in ecosystem services and feeding this information back to their economic activities. In its latest definition, SEEA-EA is: "*a spatially based, integrated statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity*" (UN 2021). The improved framework also intends to enable **thematic accounting**, by organizing data around certain policy-relevant environmental themes like **climate change, oceans, biodiversity**, etc. At the time of writing it was however, insufficiently clear whether the improved framework has met its target and refinement to the system is ongoing (Farrell et al. 2021).

Additional background and a literature overview on the evolution of environmental-economic accounting that has led up to the current SEEA-EA framework, is provided in Cavalletti et al. (2020) and Alarcon Blazquez & van der Veeren (2021).

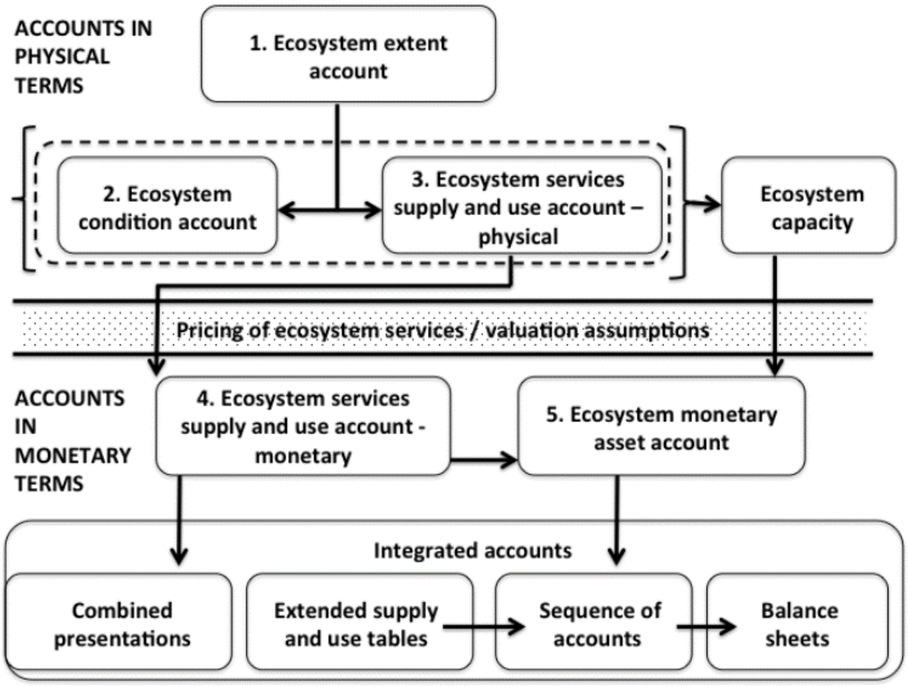

Figure 2. Relations between the different ecosystem accounts. Scheme from Graveland et al. (2017). See also (UN 2019).

3.1 Ecosystem accounting in a marine and coastal environment

Marine and coastal ecosystems play a key role in driving the global Blue Economy, our wellbeing and the fight against climate change due to the high number of socially important ecosystem services they provide (Barbier et al. 2017, Maes et al. 2020, Dauwe et al. 2021, Joliffe et al. 2021, SOPHIE-project). However, the marine and coastal ecosystems increasingly suffer from major threats like global warming (IPCC 2019), plastic pollution (Jambeck et al. 2015, IUCN) and bottom disturbing activities (Burdige 2007, Wilson et al. 2018, Alarcon Blazquez & van der Veeren 2021, Black et al. 2022). Decision-makers are thus increasingly confronted with complex challenges and pressures to balance the social, environmental and economic interests of present and future generations in our marine ecosystems (UN 2021). Taking these challenges into account, having integrated, standardised, environmental-economic accounting frameworks that keep track of the economic contribution of marine and coastal ecosystems, and in turn the impact of economic activities on those ecosystems, is considered to be highly valuable to support decision making and hence ensure a long-term sustainable Blue Economy and healthy, climate-resilient ocean

[16] The INCA-project (2015-2020) is the EU contribution to the MAES-project and intended to deliver an integrated system of ecosystem accounts for the EU (DG Environment). The final report (Vysna et al. 2021) provides an introduction to ecosystem accounting and presents ecosystem extent accounts, initial ecosystem condition accounts and ecosystem services accounts for all EU Member States (including the UK). The report showcases practical examples of possible uses of ecosystem services accounts and existing policy applications. Also a horizon scan (Weatherdon 2018) of priorities for European marine pilot accounts was developed, though it doesn't really explore blue carbon opportunities or touches upon marine shelf ecosystems.

ecosystems (Mulazzani & Malorgio 2017, Hooper et al. 2019, Hein et al. 2020, Fenichel et al. 2020, Joliffe et al. 2021, Alarcon Blazquez & van der Veeren 2021, UN 2021, Grilli et al. 2022).

The UN's latest SEEA-EA issue (UN 2021) targets to be a decisive step in this direction as it introduces the design of a set of ocean accounts. It outlines an ocean account framework that would be the first **comprehensive framework** to link relevant components of the SNA, SEEA CF and SEEA EA and harmonize priority data on the ocean, including economic, ecological, governance and social aspects. The eventual incorporation of marine ES within the UN's SEEA framework is the result of increasing pressure and effort from both global organizations (High Level Panel for a Sustainable Ocean Economy, ESCAP, GOAP[17]) and national initiatives (Graveland et al. 2017[18], Mulazzani & Malorgio 2017, Lai et al. 2018, Dvarskas 2019, Thornton et al. 2019, Hein et al. 2020, Fenichel et al. 2020) and pilot studies (e.g. MAREA-project).

Technical guidance on how to compile, use and maintain ocean accounts was provided by the Global Ocean Accounting Partnership (GOAP) in March 2022 (GOAP 2022). The guidelines were developed in response to country demands for methodological and process guidance on ocean accounting. The guidelines are in line with the System of Environmental Economic Accounting (SEEA) and System of National Accounts (SNA) and is supporting the development of the SEEA Ocean Framework. GOAP's goal is to support at least 30 countries by 2030 to build complete national ocean accounts. At the time of writing, it was yet unclear to what extent these guidelines are able to meet their objective. In the meantime, the UN approves and recommends using **ranges of physical and monetary estimates** when accounting for marine ecosystem services to take uncertainties and accounting errors into account

It is however important to remark that, the ocean accounting framework as outlined by GOAP 2022 is a new, holistic method that uses international statistical standards to integrate records of economic activities, social conditions, and environmental characteristics related to the ocean and the use of oceanic resources. The proposed ocean accounting framework is a complex systemic framework made up of economic, social and environmental components. The framework is therefore best viewed as being a compilation of different accounts that are organized according to a fixed conceptual framework. In general, GOAP's ocean accounting framework describes: (i) the interaction between economy and environment; (ii) the stock and changes in the stock of environmental assets (natural capital) that bring benefits to people; (iii) social and governance factors that affect the status and condition of environmental assets and associated benefits (GOAP, Alarcon Blazquez & van der Veeren 2021, GOAP 2022). Ocean accounts hence involve economic (e.g. SNA), environmental-economic (e.g. SEEA-EA), and social (e.g. Social Accounting Matrix (SAMs)) accounting matrices. Natural capital accounting (e.g. SEEA-EA), of which marine carbon accounting is part, is in essence an environmental-economic accounting mechanism and this sub-branch of ocean accounting makes up the main focus of this policy informing brief. A sketch of the different environmental-economic accounting principles addressed in this policy brief is given in Appendix (**9.2 Hierarchical visualisation of the accounting principles addressed**).

3.2 Marine carbon accounting

One comprehensive definition of 'carbon accounting' does not exist. Such was the conclusion of a review by Marlowe & Clarke (2022). Through a semantic analysis, it seemed the best way to define carbon accounting as being "*the recognition, the non-monetary and monetary evaluation, and the monitoring of greenhouse gas emissions on all levels of the value chain and the recognition, evaluation, and monitoring of the effects of these emissions on the carbon cycle of ecosystems*" (Stechemesser & Guenther 2012, Marlowe & Clarke 2022). By this definition, carbon accounting **considers GHG-inventories** and the monitoring and decision-making related to **climate mitigation and emission offsetting**. It can also include the monitoring of climate impacts and adaptive or mitigating measures.

Carbon accounting in general, but notably accounting of water bodies suffers from a lack of data (risk of undercounting) and methodological transparency. This often results in uncertain and incomplete GHG-inventories, effectively inhibiting a targeted monitoring and management of greenhouse gas emissions (Baltar de Souza Leao et al. 2020, Marlowe & Clarke 2022). The result is a **lack of comparable and reliable GHG-inventories** and the

[17] The Global Ocean Accounting Partnership (GOAP) is an action group of the High-Level Panel for a Sustainable Ocean Economy and is a partnership between governments, international organizations and research institutions to build a global community of practice for ocean accounting and actively stimulating the realization of SDGs 14 (Life below water), 15.9 (Valuing nature in decision-making), 17.19 (Measurement of progress complementing GDP) and other major international agendas.

[18] The marine and coastal functional unit type classification (roughly ecosystem types) are listed in Annex1, table nr.16 and 17 of UN 2019. See also Graveland et al. 2017, UN 2021, MAES-project.

potential for bias is high by entities opting to select a carbon accounting approach that is either most economical and efficient or portrays the considered entity in a positive light. Moreover, how to account for (marine) carbon sequestration and carbon sinks in accounting schemes remains **unclear and insufficiently tested**.

Since the climate mitigation potential of marine ecosystems is substantial (Dauwe et al. 2021), having a clear picture on the size and behavior of national (marine) carbon stocks and flows can be useful in the context of implementing and evaluating climate change mitigation measures. Despite the former, and the fact we rely on marine and coastal ecosystems for our welfare and wellbeing, **the size and vulnerability of marine carbon stocks and the sequestration process remains insufficiently known**, let alone being properly accounted for (Gruber 2011, Graveland et al. 2017, Keil 2017, Luisetti et al. 2019, Alarcon Blazquez & van der Veeren 2021, Marlowe & Clarke 2022). So far, the majority of the studies that estimated the economic value of marine carbon sequestration and their trade on voluntary carbon markets have focused on coastal zone ecosystems like blue carbon ecosystems (salt marshes, seagrass, mangroves) and algae (see **2.3 Blue carbon on the voluntary carbon market**) (Luisetti et al. 2011, 2013, 2014, 2019, UN 2019, Ocean Science Trust 2020, EMFF-CINEA call 2021: Algae & Climate, Alarcon Blazquez & van der Veeren 2021[19]). However, the IPCC's CO_2 reporting boundary of blue carbon ecosystems does not extend below the high-water line and CO_2 inventory IPCC guidelines[20] for other marine ecosystems like the shelf seas and the deep ocean simply do not exist. This is rather peculiar, given Article 3 of the UNFCCC clearly stating that: "*policies and measures to deal with climate change should be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation, and comprise all economic sectors*" (see also Ajani et al. 2013, Avelar et al. 2017, IPCC, EU Green Deal (COM (2019) 640), Paris Agreement (COP 21, 2015)). Marine carbon sequestration also enjoyed far less political attention compared to terrestrial sequestration pathways. To date, only the pathways mediated by blue carbon ecosystems, are included in the Nationally Determined Contributions of countries complying to the Paris Agreement (NDCs, Gallo et al. 2017, Griscom et al. 2017, Dauwe et al. 2021, Lecerf et al. 2021).

Next to a clear societal value, the **economic value**[21] of carbon sequestering marine ecosystems is **potentially very large**. It is estimated that, if the UK should lose this ecosystem service, economic damage would amount to many billions of dollars (Luisetti et al. 2019). The ES of carbon sequestration would also be worth more than half of the value of fisheries in 2018 in the OSPAR area alone (Alarcon Blazquez & van der Veeren 2021). The aforementioned estimates are likely to be an underestimation due to a conservative calculation approach, methodological limitations (e.g. shelf carbon), the conservative estimates and the limited spatial distribution data for key ecosystems providing this service.

Given the global societal welfare benefit of marine carbon sequestration, which interferes with major international agreement implications, a robust, **evidence-based governance and accounting framework** to allow for a sustainable management of different socio-economic pressures and ecosystem services is required and urgently desired (Luisetti 2019, 2020). Accounting for marine organic carbon sequestration however requires new accounting guidelines and governance frameworks for the ES to contribute to national GHG-inventory schemes and be deployed in climate mitigating measures (Luisetti et al. 2020). In its basic form the following biophysical and economic data are necessary (Luisetti et al. 2020, UN 2021, UN SEEA-EA):

- spatial extent of the habitats concerned;
- the ecosystem condition account (state/quality) measured by biophysical indicators;
- ecosystem service supply and use accounts, e.g. carbon sequestration rate (e.g. ton CO_{2e}/ha/year);
- monetary value of the provided goods and services, in this case carbon sequestration (e.g. EUR ton CO_{2e}/ ha/year);
- the ecosystem monetary asset account based on valuation of future ecosystem services (e.g. tracking changes in the carbon stocks).

In designing marine carbon accounting guidelines, one should also take **the effect of potential human disturbance**

[19] Accounting for carbon sequestration is highly relevant for OSPAR and included in marine natural capital accounts. Estimates are based on the methodology applied by Thornton et al. 2019 and focus on coastal and blue carbon ecosystems (Alarcon Blazquez & van der Veeren 2021).

[20] The EEA considers carbon accounting problematic. In the case of marine carbon accounting it advices to base calculations on terrestrial carbon accounting guidelines (Edens et al. 2019).

[21] It was estimated that damage costs of up to USD 12.5 billion from carbon release linked to disturbance of coastal (areal loss of seagrass habitats, sediment organic carbon loss from salt marshes) and shelf sea sediment (resuspension by bottom contact fishing) carbon stores could arise in the United Kingdom alone (Luisetti et al. 2019).

into account, assessed in the context of naturally occurring processes (Avelar et al. 2017, Diesing et al. 2021, Black et al. 2022).

Today, the practical application of marine carbon accounting and subsequent embedding into decision making still seems to be some way off. However, steps in the right direction are being taken (GOAP 2022) (see **3.1 Ecosystem accounting in a marine and coastal environment**). Also, at the Conference of the Parties (COP26 Glasgow 2021), contracting parties agreed to concretise the Rulebook of the Paris Agreement (Article 6), which meant making work of a robust and comprehensive accounting framework targeted for the international carbon markets. In Europe, policymakers are placing the governing of carbon dioxide removal (CDR) techniques higher on the political agenda too (COM(2021) 800, Elkerbout & Breyn 2021, Schenuit et al. 2021, EC Climate Action). Preparations are underway to integrate carbon removals into EU-climate policy by developing a regulatory framework for the certification of carbon removals based on environmental-economic (carbon) accounting rules (COM(2021) 800, Luisetti et al. 2020, Elkerbout & Breyn 2021, Schenuit et al. 2021). The aim is to adopt the framework by the end of 2022 (Certification of carbon removals – EU rules). Whether marine carbon sequestration pathways will be included remains to be seen. Until that time, the lack of clear government guidelines inhibits a top-down incentive for marine CDR techniques, leaving an important element of the marine climate mitigating potential largely untapped.

3.2.1 Accounting for marine shelf carbon

In recent years, multiple studies have looked into the size[22], distribution and content of organic carbon within marine sediments. Some examples for the North Sea area are: Wilson et al. 2018, Luisetti et al. 2019, La Rowe et al. 2020, Legge et al. 2020, Diesing et al. 2021, Hendriks et al. 2022). Still, major knowledge gaps remain with respect to the size, distribution[23] and the stability[24] of oceanic carbon stocks and flows (horizontal and vertical transport)) and how they respond to natural (e.g. changes in the water column or flow pattern) or human-induced changes or disturbances (Burdige 2007, Pusceddu et al. 2014, Turner et al. 2014, Avelar et al. 2017, Wilson et al. 2018, La Rowe et al. 2020, Black et al. 2022). This has led to a very **fragmented global picture on oceanic carbon content, carbon type and the regulating ES of carbon sequestration** (Turner et al. 2014, Avelar et al. 2017). Shallow marine areas (coastal and shelf ecosystems) in particular are considerably understudied, yet they are the most vulnerable to disturbance and are particularly important in the context of marine carbon sequestration as often they constitute major carbon sinks (Bauer et al. 2013, Turner et al. 2014, Diesing et al. 2017,2021, Avelar et al. 2017, Wilson et al. 2018, Legge et al. 2020, Black et al. 2022). However, scientific evidence suggests that the biodegradability of sedimentary carbon across shelf seas is highly heterogeneous with less sediment-bound organic matter further offshore compared to inshore or coastal sediments (Smeaton & Austin 2022). **The Southern North Sea area appears to be characterised by lower carbon densities and accumulation rates compared to the more northern regions** (Wilson et al. 2018, Legge et al. 2020, Diesing et al. 2021). The hydrological conditions in the southern section (shallow water depth, strong currents, and high wave orbital velocities) lead to a high probability of frequent disturbance of the upper sediment layer, subsequently increasing resuspension rates and decreasing long-term organic carbon storage possibilities. In other words, repeated erosion-(re)deposition cycles result in near-zero accumulation rates (Legge et al. 2020, Diesing et al. 2021). Carbon accounting of shelf sea sediments hasn't received the same attention as blue carbon accounting (see **3.1 Marine carbon accounting in a marine and coastal environment**) (Turner et al. 2014), but the number of studies that explore accounting for this ecosystem service are increasing[25] (Avelar et al. 2017, Graveland et al. 2017, Dvarskas 2019, Thornton et al. 2019, Luisetti et al. 2019, 2020). The current SEEA-EA framework also lists the marine shelf as one of its marine reference types (UN 2021) (see **3. Environmental-economic accounting**).

One of the first and few examples of an experimental application of the SEEA-EA approach in marine carbon accounting are given in Thornton et al. 2019[26] (UK). This pilot studies delivers **key empirical and methodological insight** into the complexities of marine and coastal ecosystem accounting and the inclusion of shelf sea sediments

[22] The literature often records very different estimates of the amount of organic carbon in marine sediment. This is mostly due to the use of different reference depths (0-5 cm), (0-10 cm (bioturbated layer)), (La Rowe et al. 2020) (0-100 cm) (Atwood et al. 2020).
[23] Different distinctions can be made when talking about the distribution of carbon: (i) within the oceanic system (sediment, biomass, water column); (ii) geographical distribution; (iii) the active surficial carbon cycle (biosphere) or the slow geological carbon cycle (after sequestration) (geosphere). The amount of sequestered carbon can also differ significantly between geographic regions and typically consists of a mix of marine and terrestrial sources (Bauer et al. 2013, Avelar et al. 2017, Bianchi et al. 2018, Atwood et al. 2020, Legge et al. 2020).
[24] The stability of organic carbon in marine sediments is a critical element of the global carbon cycle with close links to the Earth's climate. Insight in the different biogeochemical processes occurring with sedimentary organic carbon are given in La Rowe et al. (2020).
[25] The study of Graveland et al. 2017 conducts a pioneering study on the application of natural capital accounting on the Dutch Continental Shelf. Although comprehensive and insightful, the regulatory ES of marine carbon sequestration is not addressed in this study.
[26] The estimation of the economic value of carbon relied on the abatement cost of non-traded carbon central value provided by DECC (2017).

in the quantification and valuation of carbon sequestration and storage. One of the major issues highlighted was the **scarcity of data** from temporally or spatially, routinely replicated surveys, leading in the researchers to resort to predictive modelling as a substitute. This uncertainty had a cascading effect to other elements of the accounting exercise, like filling in the ES supply tables. Next to issues with the availability of spatial data, several challenges in defining adequate condition indicators (primary production, particulate organic carbon concentration, nutrient availability, etc.) for the marine and coastal environment were identified. In this case too, the limited data availability was regarded a hindrance (Thornton et al. 2019). Another pilot study, that applied the SEEA-EA framework at the other side of the ocean, on the coastal bays of Long Island (USA), came to very similar conclusions (Dvarskas 2019). The Dvarskas study identified three main challenges preventing reliable SEEA-EA accounting: the key issue by far was the lack of regularly collected environmental and economic data and time series; secondly, it was unclear how to define and select spatial accounting units (what is a good monitoring strategy?); and thirdly, no guidelines existed on how to upscale figures from local ecosystems to the regional or national level. In addition, questions on the **natural resource ownership** and the challenging monitoring of particulate organic carbon[27] and related carbon stock accumulated in shelf sea sediments are possible reasons as to why shelf carbon stores have **not yet been taken up in carbon credit trading schemes** and within nationally determined contributions (NDCs) (Avelar et al. 2017, NDCs) (see also **4. The main challenges with marine carbon accounting**).

4. The main challenges with marine carbon accounting

Countries that endorse the UNFCCC Climate Agreement (1992) and Kyoto Protocol (1992) are required to compile and report inventories of CO_2 fluxes from carbon sources and sinks (national greenhouse gas inventories, NGGI) based on very specific but **universal IPCC guidelines** (UNFCCC, IPCC), *de facto* rendering the IPCC as the most extensive source of carbon flow data for economic accounting purposes in the world. The IPCC acknowledges the relevance of marine carbon sequestration in the fight against climate change, but because science has not yet advanced enough to **provide effective and clear greenhouse gas accounting guidelines covering all marine ecosystems** or the entire oceanic carbon cycle, no guidelines on how to account for organic carbon stocks residing in shelf sediments exist (Avelar et al. 2017, IPCC). Countries wishing to include marine carbon fluxes into its carbon budget calculations must resort, for the time being, to ambiguous guidelines originally developed for terrestrial ecosystems[28]. Moreover, the reporting boundaries of the UNFCCC (managed vs. unmanaged land) are not applicable for marine ecosystems and they do not align to the definitions[29] used in the SNA and EEA CF[30] (see **3.1 Ecosystem accounting in a marine and coastal environment**) (Ajani 2011, EEA 2019, UN 2019).

Despite an improved framework and irrespective of the extensive preparatory study work (see **3.1 Ecosystem accounting in a marine and coastal environment**), the monetary valuation of marine and coastal ecosystems' for accounting purposes remains challenging and encounters **several limitations** (Dvarskas 2019, Fenichel et al. 2020, Alarcon Blazquez & van der Veeren 2021, Paschen et al. 2021, Grilli et al. 2022). The most plausible explanation behind the lack of marine carbon inventory guidelines and a standardised, integrative marine carbon accounting framework is the fact that marine and coastal ecosystems are generally harder to study then terrestrial ecosystems and **suffer from a lack of the appropriate spatial data on carbon stocks and fluxes**. Globally, only a limited number of value estimates are available for carbon sequestration and storage in coastal and marine ecosystems with shelf ecosystems and deep-sea ecosystems clearly less well represented than the more studied blue carbon ecosystems (see **3.2.1 Accounting for marine shelf carbon**). A feat which gravely limits the reliability and comparability of marine carbon accounting studies. Further adding to the complexity is the fact that in order to be integrative, also external and indirect influencing factors like land inputs, ocean acidification, temperature changes, changes in stratification, sea level rise, changing water currents, etc. need to be considered.

Contrary to terrestrial ecosystems, and to a certain extent blue carbon ecosystems, also a less evident **geographical demarcation** hampers a clear definition of the jurisdictional status of marine carbon sequestration within the territorial boundaries of a country, with conventional jurisdictions usually assigned to waters instead of marine ecosystem area (Luisetti et al. 2020, Alarcon Blazquez & van der Veeren 2021, UN 2021, GOAP 2022). Moreover,

[27] Studies that investigated carbon accounting of shelf ecosystems focused (mostly for practical reasons) on particulate organic carbon (POC).

[28] The carbon storage capacity by terrestrial ecosystems is universally recognised and is already widely included in international agreements and economic incentive schemes to enable their conservation and realise their local and global societal benefits (LULUCF Regulation, REDD+).

[29] Specifically, for "carbon sequestration", the SEEA EA suggests that the confusion arises because carbon sequestration and storage being two very different ecosystem services, the expression 'carbon sequestration' often includes both services.

[30] Different marine and coastal ecosystem types are distinguished within the land-cover class, and apply up to the EEZ (UN 2014, 2019).

the fact that UN SEEA relies on spatial accounting units and the fact that ecosystem boundaries do not conform one-to-one with country boundaries ensures that the boundaries of marine assets and its economic beneficiaries are generally less clear, rendering marine environmental-economic links less transparent and harder to manage by policymakers. Also, the importance to select adequate biophysical indicators that can track the state and trends of an ecosystem and its ecosystem services is an important issue (Dvarskas 2019, UN 2021). On top of this, regulating ES are **historically less recognised** compared to providing (market-based) ES like food production. As a result these ES types are still lagging behind when it comes to science, governance and management (Hein et al. 2015, Costanza et al. 2017). The importance and urgency of accounting for climate regulating ES, or oceanic ES, is however evident by the incorporation of thematic accounts in the latest UN SEEA-EA framework (UN 2021) and recent EU policy initiatives like the EC public consultation on the certification of carbon removals (see **3.1 Ecosystem accounting in a marine or coastal environment**).

If we focus on the characteristics of shelf ecosystems, we should be mindful that these ecosystems are very vulnerable to human disturbance (Pusceddu et al. 2014, Hiddink et al. 2017, Luisetti et al. 2019, Atwood et al. 2020, Legge et al. 2020). In the North Sea, because of its shallow depth and well mixed water column, any disturbance (natural or anthropogenic) in the water column or on the seafloor can **quickly change** the overall carbon stock, fluxes and storage rates and storage capacity (Burdige 2007, Pusceddu et al. 2014, Paradis et al. 2019, Luisetti et al. 2019, 2020) possibly **releasing previously buried CO_2 back in the atmosphere** within a year after disturbance (Luisetti et al. 2020, De Borger et al. 2021, Epstein et al. 2022). This is particularly relevant for human activities that affect the sea floor (e.g. dredging, trawling by commercial fishing vessels, activities related to the offshore energy sector, etc.), which are **commonplace in the North Sea**. The dynamic nature and potential significant climate implications of these activities coupled to a very specific hydrological situation, thus pose an additional challenge when trying to account for marine carbon sequestration in the area (Roberts et al. 2017, Luisetti et al. 2019, 2020, Sala et al. 2021, Black et al. 2022). Another complicating factor is the fact that the North Sea shelf is fed by carbon from terrestrial ecosystems next to inputs from the marine biological carbon pump (Legge et al. 2020). These **multiple and differing carbon sources** lead to wide variations in carbon composition (Liénart et al. 2018, van der Voort et al. 2018) and increase the risk of double counting carbon (captured and sequestered[31]) (Luisetti et al. 2020). Moreover, scientific estimates on the fractionation between the different carbon sources are currently lacking and come with significant uncertainties on burial rates or residence time (Luisetti et al. 2020). For the aforementioned reasons, it is reasonable to state that today, still many fundamental research questions remain on the so-called 'fate of the carbon' in the North Sea basin remain unsolved.

Another issue linked to the fate of the carbon question, is a **geopolitical** one. Contrary to blue carbon ecosystems, oceanic carbon in the water column is prone to move between different jurisdictions and territorial boundaries, and hence acts as a mobile 'common pool' resource (Ostrom et al. 1994). Of particular concern is the issue of ownership of the carbon stocks on the seafloor, given that not all carbon produced and stored can be traced back to its original land or maritime borders. This is especially the case in the North Sea region, where several borders are in proximity (Belgium, Holland, France, UK, Germany and Denmark) and strong currents occur. The geographic situation has important consequences for the environmental-economic accounting of net emissions and sinks, as it further increases the risk of double counting carbon capture and storage (Luisetti et al. 2020).

A final inconvenience is the notion that SEEA-EA and GOAP consider the IUCN's Global Ecosystem Typology as its reference classification system, which is not available at the OSPAR level. This is the main reason studies like Thornton et al. (2019) (see **3.2.1 Accounting for marine shelf carbon**) had to resort to the EUNIS habitat classification system. However, in the marine environment carbon processes aren't confined to the habitat delimitation used by the EUNIS system.

5. The main opportunities of marine carbon accounting

While recent efforts are increasing, applying the SEEA-E(E)A approach within a marine or coastal context, to include its ecosystem services in some measure of national performance, remains **understudied** (Mulazani & Malorgio 2017, Lai et al. 2018, Dvarskas 2019, UN 2019). Hence, marine research, which can contribute to building an understanding on how to design, fill and apply the UN SEEA-EA tables is highly valuable (Graveland et al. 2017, Dvarskas 2019, Thornton et al. 2019, Luisetti et al. 2020, Grilli et al. 2022, Marlowe & Clarke 2022). In

[31] Sequestered carbon is captured carbon that is buried on the seabed below the zone of active degradation and is the product of carbon capture/accumulation (Keil 2017, Diesing et al. 2021).

essence, expanding the fundamental knowledge base on how the complex, dynamic marine ecosystems function, next to science **addressing the debated conceptual and methodological issues** related to marine and coastal accounting are required (Avelar et al. 2017, Dvarskas 2019, UN 2021, Grilli et al. 2022) (see **4. Main challenges with marine ecosystem accounting**). Both types of knowledge are considered equally necessary if sound marine and coastal ecosystem accounting, relying on workable frameworks and science-based methodologies, is to take flight in the near future (UN 2021).

Additional pilot studies (see **3.1 Ecosystem accounting in a marine and coastal environment**) covering different marine and coastal ecosystems are put forward as a promising option to tackle this challenge (Graveland et al. 2017, Dvarskas 2019, CDRmare) as they prove very informative in identifying the required data to better chart environment-economy linkages and highlight the need for long-term monitoring. Besides the logical accretion of data, more pilots will also allow a better picture to be drawn of the target groups for SEEA-EA and how they can be catered to as the numbers of examples on how environment-economy tracking translates into decision making by its end user rises too (Graveland et al. 2017, Dvarskas 2019, Marlowe & Clarke 2022, CDRmare). Moreover, when accounting is conducted on a consistent, long-term basis, ideally across several locations, it is expected to show trends in ecosystem condition and services while also leading to more reliable greenhouse gas inventories. Such information is pivotal for stakeholders from the Blue Economy, policy, spatial planners, or conservationists with the potential to influence economic welfare and output measures, motivating targeted research or timely management action into areas of concern (Dvarskas 2019, Fenichel et al. 2020, Alarcon Blazquez & van der Veeren 2021, Gacutan et al. 2022, Grilli et al. 2022, GOAP).

In the context of climate change and marine climate mitigation, marine carbon accounting schemes can be useful to improve our understanding of climate change processes and drivers as well as their environmental-economic impact. However, they are equally likely to catalyse (marine) climate mitigating measures and maximise their effectiveness, allowing them to have an important role in working towards sustainable marine carbon cycles in the EU's economy and ecosystems (Avelar et al. 2017, EEA 2019, Fuso et al. 2019, Grilli et al. 2022, COM(2021) 800). To date, not having marine carbon removal or proven accounting frameworks is regarded as a missing key element in designing a sound, internationally accepted carbon sequestration policy. For it to succeed, it is paramount that such a framework is science-based (high measurement quality, **international monitoring standards**, unbiased reporting protocols and verification means, open access to data) and tailored to marine carbon dioxide removal by natural sinks (e.g. blue carbon) and geochemical storage (e.g. CCS)[32]. A possible way forward when designing governance frameworks for marine carbon sequestration and carbon stocks is to draw inspiration from existing guidelines of **pollutant governance frameworks** (Verleye et al. 2018, IMO), as pollutants are, just like carbon, mobile and transboundary (Luisetti et al. 2020). From a scientific perspective, having a better picture of the marine carbon cycle and its sequestration process (the 'fate of the carbon') is key (Avelar et al. 2017, Fuso et al. 2019, Atwood et al. 2020, Jin et al. 2020, Luisetti et al. 2020). In addition to providing a fundamental understanding of the marine carbon cycle, this information is also an asset in determining and drafting appropriate indicators on the condition of marine carbon sequestration and can be informative in managing the total number of indicators to a useable physical and financial level while ensuring consistency with policy frameworks such as OSPAR (1992), WFD (Directive 2000/60/EC), MSFD (Directive 2008/56/EC), the SDGs, etc.

Another concrete example in terms of marine carbon accounting is the opportunity to estimate the sustainability of economic activities on the level of their carbon emissions, rendering standardised, integrative carbon accounting useful within the framework of a.o. the European Taxonomy Regulation (Regulation (EU) 2020/852, EC Finance). This Regulation concerns a classification system established within the framework of the EU Green Deal (COM/2019/640) with the intention of redirecting private finance towards activities that support climate and sustainability goals. Next to informing on the human-climate impact, improved knowledge of SEEA-EA marine carbon accounting can also support climate finance mechanisms by for instance increasing the likelihood of the marine carbon offset trading market being regulated on the international carbon market (Sala et al. 2021, see also **2.3 Blue carbon on the voluntary carbon market**) and having marine climate mitigating ecosystem services taken up into an Emission Trading System (see **2. Pricing CO_2 emissions**). In relation to this, when properly accounted for, the carbon sequestration capacity of marine and coastal ecosystems has the potential to be eligible to be traded as 'blue bonds[33]', a financial instrument that has swiftly proven to be an effective tool to accelerate sustainable Blue Economy activities and catalyse investments towards achieving the UN SDGs (UN Global Compact).

[32] It is important to remark that marine climate mitigation can't be a "silver bullet" in the fight against climate change and that in order to limit global warming to 1.5 °C substantial and rapid emission reductions are necessary (Hoegh-Guldbergh et al. (2019), IPCC 2019, Dauwe et al. 2021).

[33] Blue bonds are a subset of green bonds (European Commission) and are defined by the World Bank as a debt instrument issued by governments, development banks or others to raise capital from impact investors to finance marine and ocean-based projects that have beneficial environmental, economic and climate benefits.

The development of standardised marine carbon accounting systems also has pre-eminently the potential to stimulate the **sharing of information and experiences** (e.g. through GOAP, OECD, Eurostat, EEA, etc.). It has been demonstrated that having measures on ecosystem processes visualised at the same time in monetary and physical terms, are likely to appeal to a larger group of stakeholders, simultaneously **increasing the trust in the observations** (Vardon et al. 2018, 2019). Ideally, efforts should be internationally coordinated to homogenise the process and maximise international comparison of accounting results (Alarcon Blazquez & van der Veeren 2021). International data standardisation and integration, like for instance a common international definition of ecosystems and ecosystem services, is likely to facilitate and optimise continuous monitoring campaigns and the identification or development of **fit for purpose ecosystem condition indicators** (e.g. carbon uptake/ha) (Luisetti et al. 2020).

Regardless of a clear potential and an increasing urgency, it is fair to state that currently the valuation of marine and coastal ecosystem services for any kind of accounting purposes still has (too) many challenges and limitations hampering the application of an integrated, standardised set of accounting frameworks (see a.o. **4. The main challenges with marine carbon accounting**). However, as a well-studied shallow shelf sea, the North Sea can prove to be the perfect **breeding ground to enhance research efforts into abovementioned challenges**, which might in time result in an in-depth understanding of the marine carbon flux, advanced carbon sequestration models, automated data analysis, or even reliable remote sensing technologies (e.g. ARIES tool). Such a realisation would mean **large gains in environmental-economic accounting** with major implications for the local climate information flow, the development of the Blue Economy and the effectiveness of protection efforts for an area that is known for its **strategic importance** and characteristic environmental conditions (see also **1.3 Advantages of the North Sea area**).

For a more in depth overview of the opportunities related to marine-ocean accounting and how they compare to marine spatial planning can be consulted in Gacutan et al. (2022) and Alarcon Blazquez & van der Veeren (2021). More on the general potential of environmental-economic accounting in decision-making, potential applications and what the practice can mean for the OSPAR region is presented in Graveland et al. 2017 and Alarcon Blazquez & van der Veeren (2021). Reflections on future research directions for carbon accounting are also included in the review paper of Marlowe & Clarke (2022). Reflections on how to improve and design future pilot studies are discussed in Graveland et al. (2017), Lai et al.(2018), Dvarskas (2019), Luisetti et al. (2019,2020), Thornton et al. (2019), Cavalletti et al. (2020), UN (2021), GOAP (2022), Grilli et al. (2022).

6. The potential of the ICOS Oceans Network

The Integrated Carbon Observation System (ICOS) forms the pillar of European greenhouse gas observations. ICOS delivers **standardised, high-precision, and long-term observations** on greenhouse gas concentrations in the atmosphere, terrestrial ecosystems and the ocean. ICOS data are already widely used by leading scientists and decision makers in better understanding climate change (ICOS). The ICOS network is part of the European Strategy Forum on Research Infrastructures (ESFRI) and currently consists of 140 measuring stations spread over 14 countries. Next to a strong terrestrial component, ICOS measures carbon concentrations in surface seawater within the ICOS Oceans Network (or ICOS Oceans Monitoring Station Assembly), coordinated by the ICOS Ocean Thematic Centre (ICOS OTC 2021, ICOS OTC). In 2022, the ICOS Oceans Network provides concentrations of seawater CO_2 in the carbon portal using 23 oceanic observation stations spread across eight countries.

The Flanders Marine Institute (VLIZ) is a partner of this marine branch of ICOS. VLIZ is contributing to the ICOS Oceans Network with two monitoring stations: the BE-FOS-Thornton buoy and the BE-SOOP-Simon Stevin. Both stations have the capacity to provide **high quality, independent and transparent long-term data for surface seawater and atmospheric CO_2 concentrations** as well as high quality physical data (temperature, salinity, dissolved oxygen) and meteo data (wind information, barometric pressure, air temperature, relative humidity). VLIZ is providing additional support to the above with frequent sampling of parameters relevant to carbon cycling such as pH, total alkalinity, dissolved inorganic carbon (DIC) and nutrients. Such observational capacity in the Southern Bight of the North Sea and the Scheldt Estuary, provides the means to **constrain the carbonate system in such a dynamic area** as well as study the air-sea CO_2 fluxes. The temporal element of this observational setup are also essential in order to evaluate the status and the variability of the carbon dynamics in this area, which can then be used as **a tool within a climate policy framework**. The scientific partnership between VLIZ and ICOS Oceans hence is an indispensable scientific alliance which local policymakers can lean on with trust to closely **monitor climate impacts for the region, as well as guiding the sustainable development of this economic important and naturally valuable area**.

Besides being firmly anchored in Europe, ICOS Oceans is also strongly embedded and active within the global observing community. The network collaborates with the International Ocean Carbon Coordination Project (IOCCP) to cover the global ocean observing systems and collaborates with the global observing community to expand a global monitoring network. One concrete example is the Surface Ocean Carbon Observation Network (SOCONET), which, among others, has resulted in the Surface Ocean CO_2 Atlas (SOCAT). ICOS Oceans also participates within the G7 *Future of the Seas* initiative, where it continues its support to the Global Ocean Observing System (GOOS) Biogeochemistry Panel as well as to several international and G7 Member ocean carbon programmes. The network is thus **perfectly positioned to make an invaluable contribution to the global challenges that are currently still prevalent around the topic of marine carbon accounting**:

- The activities of the ICOS Oceans Network and its presence in the Surface Ocean CO_2 Monitoring Network[34] will contribute to and **catalyse the development of an internationally agreed strategy for monitoring surface ocean CO_2 globally**, in turn leading to a wider spatial coverage of CO_2 measurements (e.g. SOCONET). By building on existing observing programmes, data management structures, and coordination bodies, the capability to respond to the needs of global and regional policy drivers like the UNFCCC Global GHG Stock take will significantly increase, with one of the main achievements being able to feed and **improve carbon accounting tables**;
- The ability of ICOS Oceans to collect accurate, **real-time CO_2 measurements** in a standardised way is a key asset for scientists and stakeholders to understand how much carbon the ocean captures at any given time[35]. This information is invaluable for a better understanding of the marine carbon cycle and allows for a timely **quantification of the effectiveness of marine climate mitigation measures**. Feeding this information back to policy makers and other relevant stakeholders will reduce uncertainty in marine climate mitigation measures and allow for a **more precise management** of marine ecosystems and spatial planning. All of which is very likely to lead to significant **cost savings** and an overall improvement in the state of the environment;
- Measuring surface seawater CO_2-concentrations allows ICOS Oceans to help monitor harmful marine climate change impacts like ocean acidification. For example, ICOS Oceans is an important contributor to the Global Ocean Acidification Observing Network (GOA-ON), a network designed to improve our understanding of global ocean acidification (OA) conditions, ecosystem response to OA and acquire and exchange data and knowledge necessary to optimise modelling for OA and its impacts. In connection with this, ICOS Oceans supported the SDG 14.3.1[36] data portal coordinated by the Intergovernmental Oceanic Commission (IOC UNESCO) and played a key role in developing a methodology to properly conduct acidity measurements of ocean water;
- Given their expertise on marine carbon measurements, ICOS Ocean researchers are in a prime position to improve the design of existing ES accounting frameworks, evaluate their effectiveness and **disseminate best practice approaches**. In doing so, the ICOS Oceans Network can prove to be an important driving force to stimulate and **guide the development** of internationally accepted marine carbon sequestration policy frameworks;
- Quantifying and monitoring marine carbon stocks and fluxes is a costly affair. ICOS' data collection programme allows for a **better coordination and collaboration**, compared to independent collected data by local agencies with different responsibilities, which likely serves the potential beneficiaries better and allows for a top-down and cheaper disaggregation (national-local scale) of the data;
- ICOS Ocean provides data that can be used by regional Agreements and Directives like OSPAR, the Water Framework Directive, Marine Strategy Framework Directive, etc. These data combined with the methodology and reporting principles of such frameworks would greatly **assist in the identification and correct application of appropriate environmental condition indicators** to be used in marine carbon accounting;
- The **data sharing philosophy** of ICOS can act as a stimulus to foster international collaboration, further closing the gap between national and global entities (Alarcon Blazquez & van der Veeren 2021, Grilli et

[34] This activity proposes to develop an international strategy and implementation plan that would enable G7 members and other nations to coordinate investments in a sustained, fit-for-purpose surface CO_2 monitoring network as part of GOOS. This network would build on and enhance existing global activities, principally by expanding the pilot reference network of SOCONET, in partnership with GOA-ON and the SOCAT database project and evolve with relevant Decade programmes.
[35] It can be even more informative if these data can be complemented by data on temperature, acidification, productivity, etc. (Luisetti et al. 2020).
[36] SDG target 14.3: "Minimise and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels", and the associated SDG Indicator 14.3.1 ("Average marine acidity (pH) measured at agreed suite of representative sampling stations").

al. 2022) and since all ICOS stations (in all domains) are following the same reporting principles, data from the ICOS carbon portal can be mirrored in other databases (SOCAT, EMODNet, Copernicus, etc.);

- While additional research into the ecological processes of the marine area is needed, ICOS Oceans expertise in characterising coastal and marine ecosystems and quantifying ecosystem services is invaluable to bridge the gap between current research and developing research fields like marine carbon accounting. ICOS Ocean is well positioned to **advice and provide support** in the development of new (marine) large-scale climate projects or climate research trajectories (e.g. contribution to JPI Oceans Knowledge Hub on Ocean Carbon Capacities);
- ICOS Ocean activities are well placed to **develop methods** that provide a clearer, spatially explicit picture on stocks, flows and balance of marine organic carbon and hence assist in disentangling the fate of the carbon conundrum and **verify emission reductions**;
- Given how important shelf ecosystems might be in regulating the global climate and considering the current lack of knowledge about this ecosystem, the application of the expertise within the ICOS Oceans Network to **initiate and guide** research into that area holds great opportunity;
- The continuously collected ICOS measurements can prove very informative for an early detection of changes and trends in the condition of the ecosystem (for instance the detection of remineralised organic carbon after human disturbance). This will **improve marine and coastal management** by enabling timely and targeted interventions or highlight areas of concern. At the very least ICOS OTC measurements should identify interesting areas of research.

7. Conclusions

Because of the increasing pressure on our natural environment, growing public awareness and the emergence of new economic philosophies as sustainable growth, circular economy, etc., international attention for environmental-economic (natural capital) accounting has markedly increased over the past ten-twenty years. As the knowledge and experience in applying the principle increased, so did the recognition that expressing natural assets in monetary terms **can be a key instrument in reducing or reversing global environmental threats** like climate change or biodiversity loss (Bateman et al. 2011, Graveland et al. 2017, Costanza et al. 2017, Barbier 2019, EEA 2019, Bateman & Mace 2020, Cavalletti et al. 2020, Hein et al. 2020, Dasgupta 2021, EC Climate Action).

Compared to terrestrial ecosystems, accounting frameworks covering marine ecosystem services were only properly addressed within the recently revised UN System of Environmental Economic Accounting – Ecosystem Accounting (SEEA-EA) (UN 2021) as for the first-time **outlines for the design of an ocean accounting framework were provided**. The proposed framework resulted predominantly from a series of pilot projects and leaned on expert insights and related terrestrial accounting frameworks (Hooper et al. 2019, UN 2021, GOAP 2022). This was followed up in 2022 by GOAP's Technical Guidance on how to compile, use and maintain ocean accounts. The suggested framework is designed to help nations valuing their (economic) interdependency on ocean ecosystems and in turn demonstrate the impact of economic activities on those ecosystems. Moreover, if measured in a consistent manner over a longer (uninterrupted) period, these ocean accounting tables should be able to demonstrate states and trends within the ecosystem allowing for a timely identification of common threats, targeted research, and effective management strategies (Hein et al. 2015, Barbier et al. 2017, Costanza et al. 2017, Dunford et al. 2018, Vardon et al. 2018, EEA 2019, Dvarskas 2019, Cavalletti et al. 2020). Hence disposing of a robust ocean accounting framework is considered to be a highly **valuable instrument to correlate economic-environmental linkages to policies**, which is expected to be a distinctive asset in safeguarding a long-term sustainable Blue Economy next to healthy, climate-resilient and well-functioning ocean ecosystems (Graveland et al. 2017, Mulazzani & Malorgio 2017, Hooper et al. 2019, Hein et al. 2020, Fenichel et al. 2020, Joliffe et al. 2021, Alarcon Blazquez & van der Veeren 2021, UN 2021, Grilli et al. 2022. However, for now, the robustness of the stated principles needs further testing before reliable, comparable ocean accounting practices can take place (Fenichel et al. 2020, Farrell et al. 2021, UN SEEA-EA).

In the context of marine climate mitigation, **carbon dioxide removals** (CDR) from marine ecosystems (blue carbon, marine afforestation, marine geoengineering) or industrial solutions (e.g. Carbon Capture and Storage (CCS)) (Dauwe et al. 2021), call for **strong requirements on monitoring, reporting and verification** if they are to be recognised as a contribution to EU's climate or environmental objectives and taken up into national carbon budgets. A challenge that could be answered by the development and use of a fully **transparent, science-based and universal marine carbon accounting system** (Bianchi et al. 2018, Luisetti 2019, 2020, Black et al. 2022, COM (2021) 800, EC public consultation on the certification of carbon removals). To date, the economic valuation of marine carbon sequestration and the trading of marine carbon on voluntary carbon markets have focused predominantly on coastal blue carbon ecosystems (Luisetti et al. 2011, 2013, 2014, 2019, UN 2019, Ocean Science Trust 2020, Verra, Plan Vivo). Lesser-known ecosystems like shelf-sea ecosystems (<200 m depth) are also often characterised by large burial rates of organic carbon, sizeable but, importantly, stable carbon stocks. Shelf ecosystems are, just like blue carbon ecosystem, thus potentially very **valuable in terms of climate regulation** and the organic-rich sediments on the seafloor should be serious **contenders for carbon credits**. However, the ecosystem suffers from **sparse data** on local carbon stability and accumulation rates (Avelar et al. 2017, Luisetti et al. 2019, 2020, Atwood et al. 2020, Legge et al. 2020, Diesing et al. 2021, Sala et al. 2021). Also major **questions on the movement of organic carbon through the system** (fate of the carbon) still remain and how it is affected by natural or anthropogenic factors, such as seafloor disturbance (Burdige 2007, Pusceddu et al. 2014, Turner et al. 2014, Avelar et al. 2017, Fuso et al. 2019, Atwood et al. 2020, Jin et al. 2020, La Rowe et al. 2020, Luisetti et al. 2020, Diesing et al. 2021, Black et al. 2022). In general it is fair to say that overall the size and vulnerability of marine carbon sinks and the sequestration process remains inadequately understood, with **insufficient marine carbon accounting projects** to address critical methodological and policy concerns (Gruber 2011, Turner et al. 2014, Avelar et al. 2017, Keil 2017, Dvarskas 2019, Luisetti et al. 2019, 2020, Thornton et al. 2019, Cavalletti et al. 2020, Alarcon Blazquez & van der Veeren 2021, Marlowe & Clarke 2022).

Our North Sea, which is a well-studied but at the same time heavily used (disturbed) shallow shelf sea, can prove to be the **perfect breeding ground** to enhance research efforts into marine carbon cycling and designing sound accounting principles for marine carbon sequestration ecosystem services. Hence, it can serve as an ideal pilot for European policymakers and stakeholders to push for the development of a fit for purpose marine carbon accounting system and **marine carbon dioxide removal incentivizing policy frameworks** (Avelar et al. 2017, Fuso et al. 2019, Dvarskas 2019, Luisetti 2019, 2020, Thornton et al. 2019, Alarcon Blazquez & van der Veeren 2021, Grilli et al. 2022, EC public consultation on the certification of carbon removals). Such a realisation would mean **large gains for the universal concept of marine carbon accounting** and have major implications for area-specific climate mitigation strategies, **marine spatial planning** and the sustainable growth of the Blue Economy and the effectiveness of protection efforts for an area that is known for its economic importance and characteristic environmental conditions.

For this scientific-political endeavor to have a proper chance of success, it is paramount that stakeholders can rely on a well-developed, broad **scientific knowledge base** (Verleye et al. 2020), open-source high-quality observation data (e.g. EMODnet), ideally conforming to international monitoring standards, with unbiased reporting protocols and clear **objective verification means** (COM (2021) 800, UN 2021, Alarcon Blazquez & van der Veeren 2021, GOAP 2022, Grilli et al. 2022). A great opportunity to meet the above preconditions and maximise the potential of marine carbon accounting is to rely on the expertise and infrastructure of the **ICOS Oceans Network**. The ability of ICOS Oceans to collect accurate, **real-time measurements on marine carbon concentrations** in a standardised way is a key asset for scientists and policymakers to elucidate 'the fate of the carbon' mystery. ICOS Oceans extensive experience in marine carbon monitoring puts the network well-placed to improve the design of marine carbon accounting frameworks, evaluate their effectiveness and disseminate best practice approaches. In addition, ICOS Oceans expertise can provide the basis for developing regulatory marine carbon sequestration frameworks and thus **further facilitate the development of marine climate mitigation**. Relaying this information to policy makers and other relevant stakeholders will reduce uncertainty in marine climate mitigation measures and allow for a more precise management of marine ecosystems and spatial planning. In other words, the ICOS Oceans Network holds some promising but still uncapped opportunities to support society in its climate fight. In Belgium the ICOS Oceans Network relies on **state-of-the-art research infrastructure** of the Flanders Marine Institute (VLIZ) to conduct its observations.

It is however clear that the concept of marine carbon accounting requires **extensive cooperation** and good communication between different stakeholders to represent the diverse economic, environmental, and social interests in the **most balanced way possible** and thus ensure long-term **sustainable development** (UN 2019).

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9. Appendix

9.1 The social cost of carbon (SCC)

The social cost of carbon (SCC) is calculated by scientists to monetarise the incremental unit of carbon emissions and is used to assess climate policies (Wang et al. 2019). The social cost of carbon (SCC) can be understood as the marginal global damage cost (expressed in USD), or the change in the discounted value of economic welfare, caused by the emission of one ton of CO_2 (Watkiss 2006, Cai et al. 2017, Nordhaus 2017, OECD 2018, Wang et al. 2019). It is a metric that indicates how much society is willing to pay today to avoid future climate damage and as such it is used to assist policy makers to determine whether the costs and benefits of a proposed climate mitigating measure are justified (the higher the SCC, the more positive the opinion to implement the measure). The SCC has become a key tool, predominantly used by US federal government agencies, in the determination of regulatory policies that involve greenhouse gas emissions. Determining the SCC is a complex, model-based procedure and widely alternative approaches are used to calculate it (Wang et al. 2019). However, four types of data are included in the models by default: climate projections, socio-economic projections, benefits vs. costs, and the discount rate[37]. Currently, there are few established integrated assessment models (IAMs) able to estimate internally consistent SCC figures and all of them are flawed as they base their calculation on a large amount of uncertain and (yet) unquantifiable elements. On top of that, IAMs inherently contain political and moral judgments. In reality, IAMs produce a range of figures coming with large variation. For practical reasons, one central CCS-value is chosen, which is the average of the range at a selected discount rate. The metric is however strongly influenced by economic and climate risks, and so the potential to heavily influence policy makers when weighing up interactions between the climate and the economy (Cai et al. 2017, Nordhaus 2017, OECD 2018). It is important to point out however that the use and value of the SCC is increasingly debated between economists due to its subjective nature and rather poor qualitative value. Moreover, its effectiveness in reducing GHG emissions isn't unequivocally demonstrated. Kaufman et al. (2020) suggest that it is better to use the SCC in proposing a carbon tax, coupled to a clear timeframe for achieving legally binding emission reduction targets (just as is currently the case in the EU and the UK). Such an approach would significantly reduce the uncertainties related to estimating the cost of global future damage caused by climate change. The social cost of carbon was estimated at 51 USD (February 2022).

[37] The discount rate indicates the rate at which society is willing to trade present benefits for future ones. A high discount rate implies that people more greatly value the money in hand, spending less today to allow future generations to bear more of the costs.

9.2 Hierarchical visualisation of the accounting principles addressed

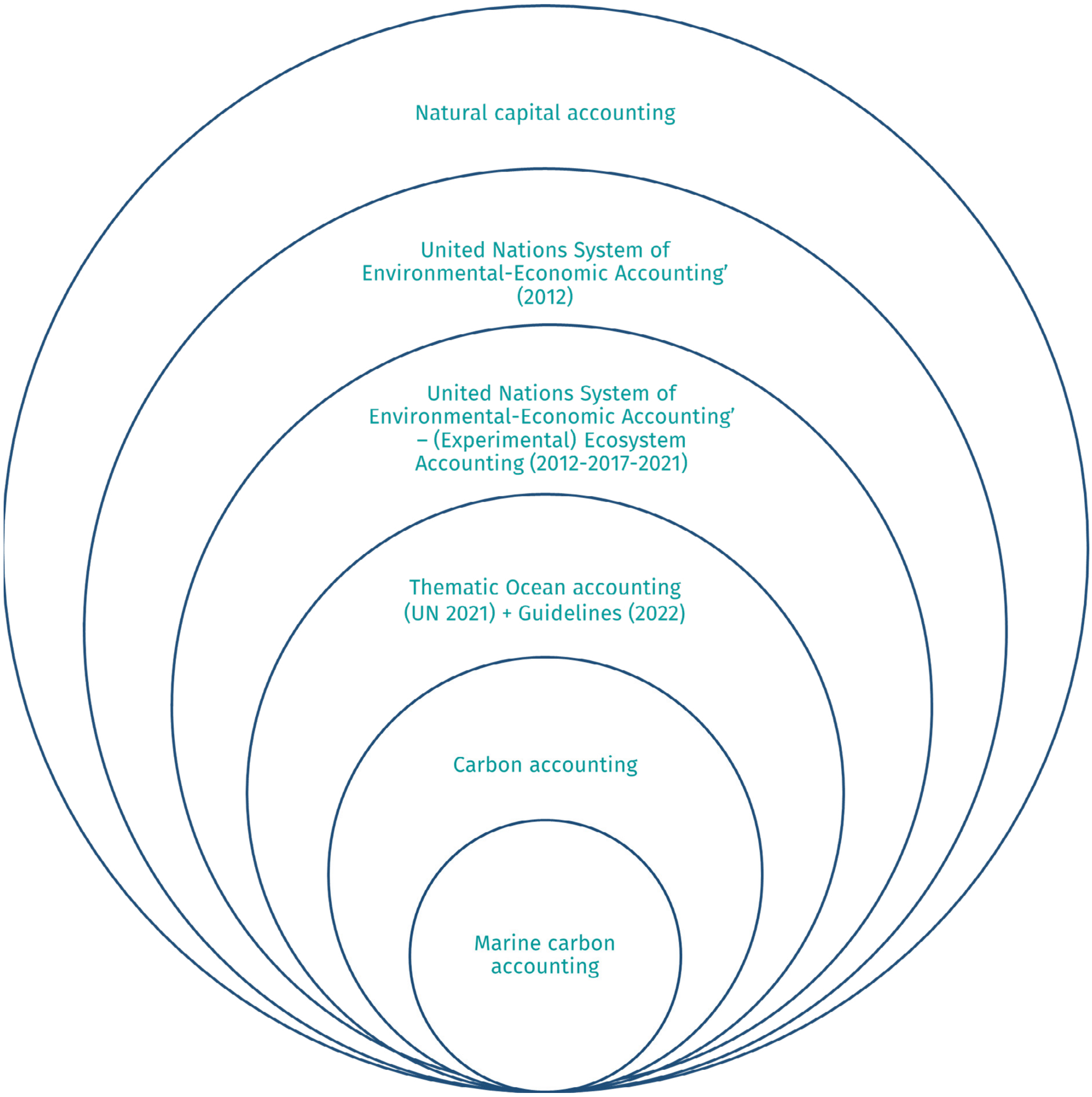

Figure 3. Hierarchical classification of the different types of environmental-economic accounting addressed in this policy brief. Note that the technical guidelines by GOAP go beyond the ecosystem accounting principle (see **3.1 Ecosystem accounting in a marine and coastal environment**).